ANNUAL CONFERENCE ON FIRE RESEARCH
Book of Abstracts
November 2-5, 1998

Kellie Ann Beall, Editor

Building and Fire Research Laboratory
Gaithersburg, Maryland 20899

NIST

ANNUAL CONFERENCE ON FIRE RESEARCH
Book of Abstracts
November 2-5, 1998

Kellie Ann Beall, Editor

October, 1998
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

Three Dimensional Radiative Ignition and Flame Spread over Thin Cellulose Fuels

S.L. Olson, NASA Lewis Research Center
T. Kashiwagi, National Institute of Standards and Technology

Abstract

Radiative ignition and transition to flame spread over thin cellulose fuel samples was studied aboard the USMP-3 STS-75 Space Shuttle mission in February and March of 1996, using the RITSI hardware. A focused beam from a tungsten/halogen lamp was used to ignite the center of the fuel sample while fan-drawn air flow was varied from 0 to 6.5 cm/s. Non-piloted radiative ignition of the paper in air was found to occur more easily in microgravity than in normal gravity. Ignition of the sample was achieved under all conditions studied, with transition to flame spread occurring for all but the quiescent flow condition. After ignition, the flame spread only upstream, in a fan-shaped pattern. The fan angle increased with increasing external flow from zero angle (tunneling flame spread) at the limiting 0.5 cm/s external air flow, to 90 degrees (semicircular flame spread) for external flows at and above 5 cm/s. The downstream flame is inhibited due to the 'oxygen shadow' of the upstream flame, despite the convective heating from the upstream flame. Only after the upstream flame spread was complete could downstream flame spread occur.

Ignition

Radiative ignition was achieved easily in microgravity, unlike normal gravity where the irradiation alone was insufficiently energetic to ignite the quickly-convected hot degradation products over a vertical sample surface. Ignition delay times varied linearly with inverse iflow, as shown in Figure 1. The slower the flow, the longer the ignition delay time. This dependence is believed to be due to gas-phase mixing times, which are also inversely proportional to the imposed flow. Ignition is quite energetic; a thermal expansion wave from the ignition event easily exceeds the imposed flow and is quickly sensed by the thermocouples both upstream and downstream of the ignition spot. The crew, monitoring the experiment visually, commented "There was a great burst of flame perpendicular to the surface." and "I can peak inside and I can tell you that it's incredible: they're really 3-D."
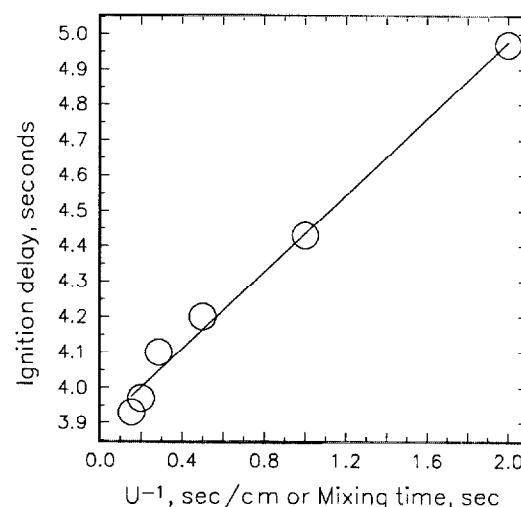

Figure 1: Ignition delay varies with the inverse flow

Flame Spread

Flame spread from a central ignition spot is unique in that the flame in this situation can go in whatever direction(s) it finds conducive to spread. The resultant direction(s) are revealing about the important controlling mechanisms for flame spread in this weakly ventilated microgravity environment. Ignition in a quiescent environment occurred, but transition failed and the flame extinguished. With flow, transition to spread only occurred in the upstream direction as shown in Fig 2. Despite convective heating, the downstream region was not flammable due to the 'oxygen shadow' cast by the upstream flame. The incoming oxidizer was consumed by the upstream flame, and the combustion products from that flame were swept downstream. The downstream flame, unable to obtain sufficient oxygen in the vitiated flow, was not viable. The flame spread only upstream until the edge of the sample was reached. At that point, once the upstream flame was gone, the flame wrapped around along the unburned edges of the sample and a concurrent flame (Fig.2d), now able to obtain unvitiated oxidizer flow, began to spread. These preliminay downstream flame spread rates are more difficult to measure because of this non-ideal geometry.

a)0.5cm/s   b)2cm/s
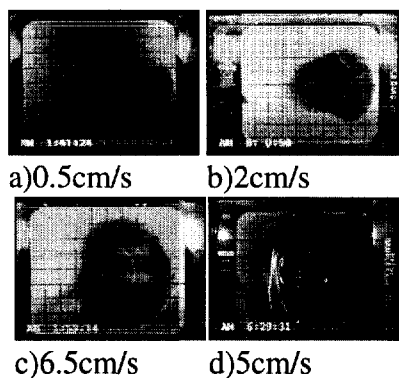
c)6.5cm/s   d)5cm/s

Figure 2

Flame spread rates were measured in each test for both the upstream and later for downstream flame spread. At the lowest flows tested (0.5 and 1 cm/s), viable flame spread occurred only in the upstream direction. The measured flame spread rates are plotted in Figure 3, where upstream flame spread flows are positive and downstream spread flows are negative. Symbols are sized to represent the scatter in the data from the least squares regression line through the data. The quench region is indicated in Fig 3, generally centered around quiescence but skewed to the downstream side. Simultaneous upstream and downstream flame spread was not observed over the flow range studied. Upstream (opposed-flow) flame spread is faster than downstream (concurrent) flame spread at a given flow over the range of flows studied due to this skewing. These results agree qualitatively with model predictions [1]. Faster upstream flame spread is the exact opposite of normal gravity flame spread where not only is simultaneous upward (downstream) and downward (upstream) flame spread possible, but the downstream flame spread is much faster.
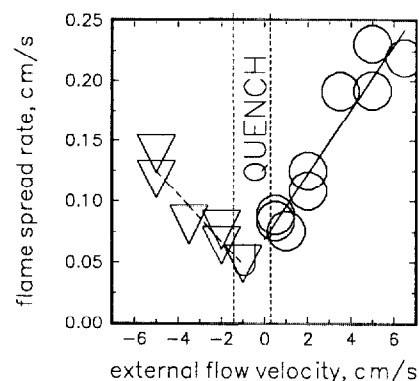

Figure 3: upstream and downstream flame spread

3D Limiting Flame Angles

The upstream flame spread propagated radially from the ignition region. However, there appears to be a maximum angle of flame spread for a given flow. This maximum fan angle of the propagating flame front can be seen in the char patterns in Fig 2. The experimental angles, defined as the angle from direct upstream motion to the edge of the char region, were measured from the video images. The measured values are shown in Fig 4 as a function of flow. At sufficiently high flows (>3.5 cm/s), the flame angle is nearly 90 degrees, indicating semicircular flame propagation in the upstream direction. Below that flow, however, the flame angle reduces with flow until a limit of zero angle is reached at 0.5 cm/s flow. The flame at 0.5 cm/s propagated directly upstream without any lateral growth. A quiescent flow case extinguished shortly after ignition, so the 0.5 cm/s flow case is very near the extinction limit.

Figure 4: flame angle increases with flow

A simple analysis estimates the flow normal to the flame front to determine the limiting flame angles at which the normal flow (with diffusional flow, U_D, superimposed) becomes the limiting value of 0.5 cm/s, to be $\alpha_{lim} = \cos^{-1}[(U_{n,lim} + U_D)/(U + U_D)]$. Curves of this equation are shown in Figure 4 for values of U_D of 0, 1, and 2 cm/s. Good qualitative agreement is obtained at the higher flow rates (convective regime) when diffusion is neglected ($U_D=0$), but the importance of diffusion is pronounced for the flows at and less than 2 cm/s (diffusive regime), where qualitative agreement is good only when a $U_D=2$ cm/s is used. Simply estimating the oxidizer flow normal to the flame front is sufficient to reasonably predict the limiting spread angle.
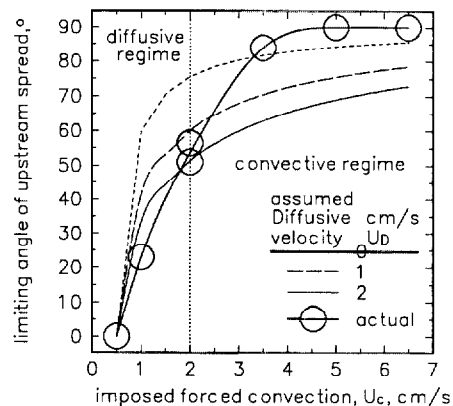
Conclusions

Radiative ignition occurred more readily in microgravity than in normal gravity. The ignition delay time is linearly dependant on the gas-phase mixing time. After ignition, flame spread occurred only in the upstream direction, indicating a strong need for fresh oxidizer. The angle of the flame as it spreads upstream is shown to be directly related to the limiting flow velocity normal to the flame front. A downstream flame is not simultaneously viable due to an 'oxygen shadow' of the upstream flame. Once the upstream spread is complete, a downstream flame becomes viable and concurrent flame spread occurs.

References

[1] McGrattan, K.B., Kashiwagi, T., Baum, H.R, and Olson, S.L., Comb. Flame 106, pp. 377-391 (1996).